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Multi criteria site selection model for wind-compressed air energy storage power plants in Iran

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ABSTRACT

In this research, a site selection method for wind-compressed air energy storage (wind-CAES) power plants was developed and Iran was selected as a case study for modeling. The parameters delineated criteria for potential wind development localities for wind-CAES power plant sites. One important consequence of this research was the identification of the wind energy potential for wind-CAES sites. The theoretical wind energy potential of Iran of greater than 50 W/m^2 was identified from a wind atlas of Iran. The model produced factor maps by considering the boundary conditions of the input data and created geo-databases from the outputs maps. The main factor maps were electrical grids and substations, gas transmission lines, a wind energy atlas, thermal power plants (location and capacity), salt dome locations and extends (for compressed air reservation), slope data, a digital elevation model, cities and residential areas, water bodies and access roads. For every data layer, criteria where developed from existing laws, regulations and scientific studies and normalized for Iran. In the final step of analysis and modeling, the factor maps were integrated by coding using ArcGIS software and the wind-CAES power plants sites were selected. This research showed that 30 sites in 5 major zones have the capability to support installation of wind-CASE power plants in Iran.

Contents

1. Introduction

Energy is a driving force for global social, economic and technological development. Fossil fuels are the dominant available global resource and play a crucial role in supplying mankind's increasing demand for energy. Fossil fuel reserves are limited, however, and their use has negative environmental impacts. The present rate of energy consumption of energy is high and fossil-based resources cannot continue to provide energy at their current rate; these resources will be used up in the relatively near future. Renewable energy is expected to play an important role in handling the demand for energy and reducing environmental pollution [1].

Since the first oil crisis, renewable energy sources have been discussed as renewable, sustainable, and environmentally friendly

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forms of energy. Geothermal, solar and wind-based renewable energy sources have the potential to reduce dependence on fossil fuels for electricity and reduce greenhouse gas emissions [2]. The role of renewable energy sources for electricity has improved and they are considered alternatives for replacing fossil fuels for power production because of increased public awareness of the negative environmental impacts of conventional power-generating methods, such as coal- and oil-fired plants.

Wind energy is a reliable and promising form of renewable energy. It is currently a significant, fast growing, commonly-used and commercially attractive resource. It has become more attractive as a clean renewable energy resource because of the maturation and cost-effectiveness of energy conversation technology. The installed capacity of electricity generation from wind energy is rapidly increasing in countries that are implementing a variety of incentive policies and, thus, the importance of wind energy is expected to increase in the coming decades [3]. The cost of electricity generation from wind energy has become competitive with that of electricity from fossil fuel power plants. This makes wind power a popular and safe form of renewable energy that can be economically viable, does not produce significant environmental pollution, and can contribute significantly to the reduction of CO_2, NO_x and SO_x.

Novan measured the decrease in CO_2, NO_x, and SO_2 production from electricity supplied by wind turbines in the Texas electricity market. He found clear evidence that renewable generation in the region offset significant amounts of each of the pollutants examined. The average pollution offset by a MWh of renewable electricity is 0.54 to 0.93 t of CO_2, 0.88 to 1.92 lb of NO_x, and 0.97 to 4.30 lb of SO_2 [4].

The wind energy is expected to play a major role in fulfilling the recent targets set by national policy in Iran. This energy is attractive for planners and developers because of its lower energy, environmental and social costs that minimize the dependency on fossil fuels and improve the economy and lifestyles of remote areas. Because wind energy is a clean and renewable energy source, in the global context of increased social concerns about climate change and energy supplies, it has experienced strong and stable levels of public support.

Despite the advantages, the intermittent nature of wind energy remains a challenge and efforts are ongoing to find a solution. One solution is the storage of electricity from wind turbines as compressed air in underground caverns. In this technique, off-peak electricity produced by wind turbines is used to run air compressors used to fill underground mines, abandoned oil and gas wells or salt domes with compressed air. In the absence of wind or at peak times, the compressed air is released to a gas turbine that produces electricity with higher efficiency to meet grid demand.

Identifying suitable areas for such underground structures to store compressed air in areas with adequate wind resources and other criteria is a complex task. Location-based decision-making by integration of the results of surveys and studies is a procedure subject to human error. Geographical information systems (GIS) can be used as digital location-based computation tools to minimize errors by identifying prospective areas using digital thematic maps [5] and conceptual models for data integration [6].

The focus of this paper is to find the most suitable locations for wind-CAES development as a peak-shaving tool in Iran. Wind-CAES site selection is an innovative method of applying technology to wind energy; the method locates suitable locales with suitable geology and reservoirs available to hold air at pressures of less than 90 bars [7] to operate CAES-powered gas power plants. The practicality of the issue in this context is one of economic viability.

A utility company would only build a wind-CAES plant in Iran if all requirements could be easily obtained and utilized. Wind-CAES makes economic sense over other options to mitigate problems associated with intermittent wind. This paper examines how to use GIS integration models for a wind farm and CAES plant site selection.

2. Wind compressed air energy storage

Management of the energy supply using renewable energy generators can be achieved by energy storage. Despite the lack of significant new construction, interest in energy storage did not completely cease when the cost of fossil fuel dipped. Research and development has continued, along with an increasing number of proposed projects [1]. Recent renewed interest in energy storage has been motivated by at least five factors:

- Advances in storage technology.
- An increase in fossil fuel prices.
- The development of deregulated energy markets, including those for high-value ancillary services.
- Challenges to siting new transmission and distribution facilities.
- The perceived need and opportunities for storage using variable renewable generators [1,8].

Energy storage increases the technical reliability of the power supply, stabilizes the cost of electricity and helps to reduce greenhouse gas emissions, but electrical energy storage presents difficult engineering and scientific obstacles that have not been fully overcome. Consumers are still waiting for batteries that last longer and utilities have been searching for affordable large-scale storage that will allow them to run generators at a constant rate rather than ramping up and down with demand. The increased use of intermittent renewable resources (wind and solar) adds another level of complexity for utility companies [9].

Storing large amounts of electrical energy in a cost effective and efficient method remains a difficult challenge. The advent of modern renewable energy sources improves the ability to collect or harvest energy, but not to store what is gathered. Modern renewable energy sources intensify the search for robust, cost-effective means to store energy. Intermittent energy sources such as solar panels or wind turbines require energy storage capacity if they are to provide consistent, on-demand power to the user and be able to replace traditional fossil-fuelled systems [10].

The major options for utility-scale energy storage are CAES, pumped hydroelectric energy storage, different types of batteries, flywheels, superconducting magnetic energy storage (SMES), and ultracapacitors [10]. The technology chosen is generally a function of the duration of storage, as indicated below:

- Long duration storage (>10 h): pumped hydro.
- Intermediate duration storage (4–10 h): compressed air.
- Short duration storage (<3 h): batteries, SMES, and flywheels [10,11].

Large scale energy storage systems are one solution. One of the most promising forms of large scale storage is CAES, which is an inexpensive way to store massive amounts of energy for long periods of time. Aside from pumped hydro storage, compressing air when power is inexpensive and plentiful and then using it to boost natural gas-fired power turbines during peak demand is the only way to shift hundreds of megawatts of load from 1 hour to the next [11–13]. CAES plants save a region's abundant wind power for later use, when demand is high and power supplies are more costly.

CAES is designed to store off-peak energy for use during peak demand periods. During off-peak periods, a motor operates on excess power to compress and store air in subsurface formations.

During peak load periods, the process is reversed, allowing the already compressed air to return to the surface and drive turbines as the air is slowly heated and released. No additional compression is necessary to drive the turbines because enthalpy is included in the compressed air [14]. These plants switch between energy storage and power generation within minutes, providing the flexibility to balance a region's variable wind energy generation throughout the day. CAES plants can regenerate as much as 80% of the electricity they take in [15]. Fig. 1 shows the configuration of the wind-case system.

3. Wind energy potential in Iran

Iran's wind potential indicates several good to very good regions of interest for further wind farm development. Table 1 shows the theoretical wind energy potential of the atmosphere at $>50\ \mathrm{W/m^2}$, $>100\ \mathrm{W/m^2}$ and $>150\ \mathrm{W/m^2}$ in Iran.

The table shows that the use of mountainous slopes is restricted to less than 10%, leaving the energy potential of approximately 143 GW remaining for wind power development. Only 20% to 30% of this required area may be easily available because of limited network access and or previous infrastructure or environmental restrictions. This results in a feasible potential of approximately 30 to 40 GW, which meets most of the electricity requirements for Iran. Note that the area in column one of the table comprises all terrains [16]. Iran had a total installed electricity generation capacity of 65 GW at the end of 2012 (up from 90 MW in 1948 and 7024 MW in 1978) [19,20].

The calculations are based on numerical flow simulations using the KLIMM 3D atmospheric model that has been designed to take into account the complex structure of the terrain (topographic elevation and land use distribution). The KLIMM model used in the Iran wind mapping project is a 3D numerical mesoscale model of the atmosphere. The model allows simulation of the wind at any point in the atmosphere. Analysis of typical weather, locally measured wind resource data, and the results of KLIMM can be used to calculate the long-term annual wind speed for any location. KLIMM has been already applied successfully in a variety of wind mapping projects [16]. The model simulations employed the following input data:

- Geodetic height data (digital terrain model).
- Land use maps (digital raster data).
- Information on geostrophic wind conditions and air temperature stratification.
- Wind velocities at wind measurement stations.

For verification and fine adjustment of the calculated results, data from 130 wind measuring stations distributed across the area (measuring at heights of 10 to 40 m above ground) were used. A digital numerical model of the survey area was created showing topographic elevation and land use data with a grid size of 200 m in resolution. Computational flow calculations were performed for distinctive representative meteorological scenarios. Results of the individual scenarios were combined into representative annual mean wind speed depending on the statistical frequency for each scenario.

The calculated and measured wind speeds were correlated (cross validation) at representative locations. On the basis of these fine adjustments of the 3D wind fields, the spatial distribution of the annual wind velocity was determined for the total area. The resulting wind map shows wind speeds and wind power density at a heights of 50 m and 80 m, which was equivalent to the hub heights of state-of-the-art wind turbines. The data covered a wind measurement campaign of at least 24 months. The KLIMM model flowchart is shown in Fig. 2.

As seen from the computed and available technical wind potential, most electricity demand in Iran could be covered solely by wind energy if network access, transmission, distribution, and electricity storage by pumped hydro power plants and wind-CAES allowed. The existing power distribution system is adequate to distribute electricity from the selected wind farm sites to the initial applications. The wind farms may feed electricity either to the existing grid or to isolated local networks for up to 20% of electricity demand. Larger shares of wind energy may be required at points with more frequent load shedding and may require network extensions or electricity storage options [16]. Fig. 3 shows the wind speed map at 80 m for Iran.

4. Methodology

The primary requirement for locating a CAES plant is geological suitability for a storage cavern for compressed air. Additional requirements are that the noise produced by the CAES turbine will not annoy nearby residents and that the site must have access to an adequate source of natural gas to power the thermal power plant. These factors limit site selection somewhat, but are secondary concerns to the main issue of suitable geology [9].

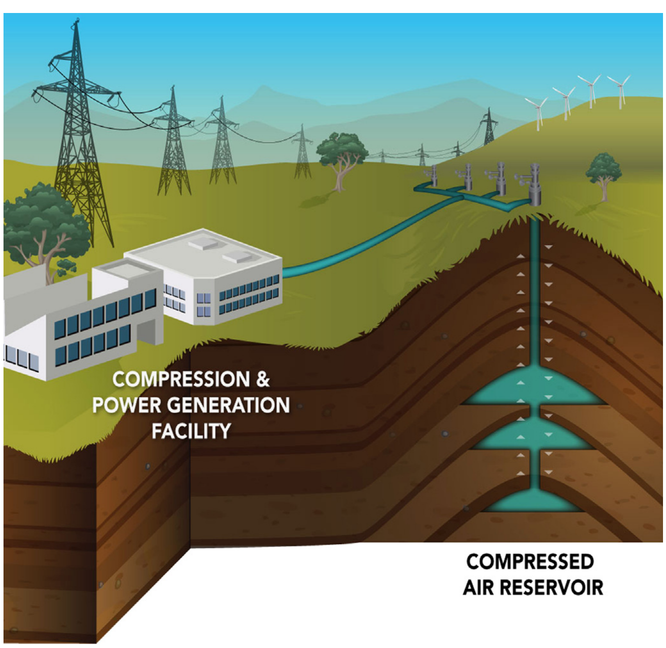

Fig. 1. The configuration of the wind-case system.

Table 1
Theoretical wind energy potential of Iran based on atmospheric analysis.

	Units	$>50\ \mathrm{W/m^2}$	$>100\ \mathrm{W/m^2}$	$>150\ \mathrm{W/m^2}$
Coverage rate	%	80.9	38.4	9.6
Area (1,500,363 $\mathrm{km^2}$)	$\mathrm{km^2}$	1,214,294	576,077	145,138
Energy potential	GW	725	450	152
Energy potential in area with mountainous slopes less than 10%	GW	–	–	143

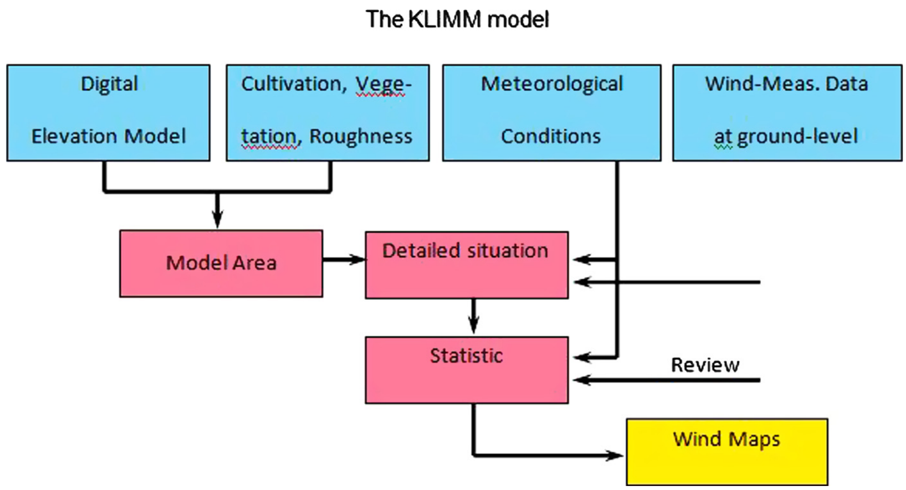

Fig. 2. The flowchart of the KLIMM model.

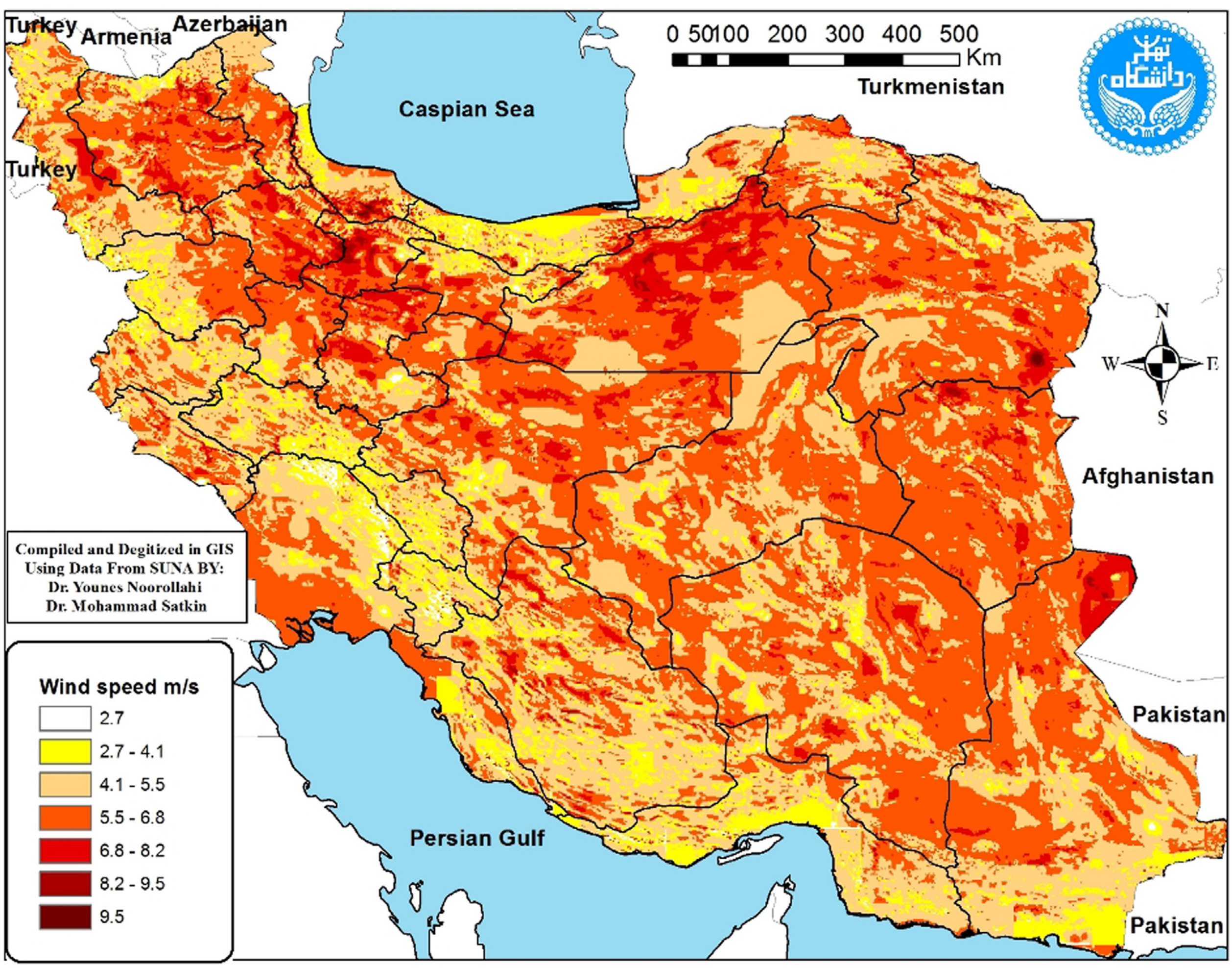

Fig. 3. Iran wind speed atlas in 80 m height.

A main factor for wind-CAES site selection is to identify windy areas that possess the previously described qualities. The area under initial analysis may be as large as a utility service territory or an entire province, so the site selection process should be designed to efficiently focus on the most suitable areas [15,19]. All the parameters for site selection were considered using three main sub-models and individually analyzed using ArcGIS Boolean logic algorithms. The final overlay techniques resulted in three promising maps that intersected and defined suitable wind-CAES power plants sites. The wind-CAES power plants sites met specific requirements in three main categories:

- Wind energy resource and grid connection availability.
- Thermal power plant and energy storage potential.
- Environmental and economic suitability.

In the first sub-model, the whole country was analyzed and suitable locations were defined based on data and criteria shown in Table 2 that are used globally for wind-CAES site selection and were normalized for Iran. The results of this sub-model defined the locations having wind potential and possible connections to substations and the national power grid.

The second sub-model defined locations as suitable if they met several requirements. The first was the availability of a natural gas pipe line to supply the fuel for the power plant. Installing a new gas pipeline increases project cost. Next is the existence of sites for the thermal power plant and availability of a cavern for storing the compressed air. Locating a reservoir was the more difficult challenge. Although there are many potential types of CAES reservoirs [17], only salt domes were defined as potential reservoirs for this study. The data and criteria for wind-CASE site selection are shown in Table 2.

The third is an environmental-economic sub-model that applies regulatory criteria when selecting the best available locations. All residential areas (cities, villages and individual structures) were evaluated for negative impact from the wind turbines, the compressed air and the thermal power plants. Areas with slopes greater than 15% were discarded because of national regulations. Locations with elevations higher than 2000 m are also discarded because of impact of lower air density on wind power output. Access roads are an economic parameter that can increase project cost if an adequate road is not available. Fresh water is also required to create a cavern in a salt dome, and should be available for transport from a nearby location. The environmentally protected areas are discarded from site selection in addition to a predefined buffer zone based on national regulations. The main input data, criteria and reference areas used for site selection modeling are shown in Table 2.

Wind turbine efficiency decreases at elevations over 2000 m, so the maximum acceptable slope for the wind power plants sites (S) was 15% and maximum elevation (H) was 2000 m [15]. Water is required to create a cavern in a salt dome. Since the water supply is only required at the time of construction, it can be transported by tankers from nearby water sources. The maximum allowable distance between the water source and the site was 50 km.

5. Data integration and suitable site selection

The three sub-models were analyzed to specify suitable sites for wind-CAES power plants. The three factor maps were modeled for integration using ArcGIS software.

5.1. Wind energy resource and grid connection availability

In the first stage of modeling, the criteria in Table 2 were applied and factor maps prepared as GIS data layers. These factor maps were electrical grid transmission line for grid connection (GCF), power substations (SF), and windy areas (WF). The factor maps were integrated to specify windy sites located within the boundaries of electrical grid transmission line with access to substations. The limitations were buffered in the model and the factor maps merged. The output of this stage was labeled wind energy availability (WEA) or Factor Map 1 and is defined in Eq. (1)

Table 2
Wind-CAES site selection criterion in three sub-models.

No.	Sub-model	Subject	Max. allowable distance	Min. allowable distance (km)	Refs.
1	Wind energy resource and grid connection availability	Windy areas (W)	inside	–	[6]
		Electrical Grid transmission line (GC)	10 (km)	0.250	[11]
		Substation	10 (km)	0.250	[11]
2	Thermal power plant and energy storage possibility	Gas transmission line (GT)	20 (km)	0.500	[14]
		Salt dome (SD)	2 (km)		[14]
		Thermal power plants	10 (km)		[11]
3	Enviro-Economical suitability	Cities and Residential locations (CL)	–	2	[11,12]
		Access roads (AR)	10 (km)	0.250	[11]
		Water bodies (WB)	50 (km)	0.500	[15]
		Environmental protected area (EP)		2	[13,16]
		Slope (S)	15 (%)		[5,17]
		Elevation (H)	2000 (m)		[5]

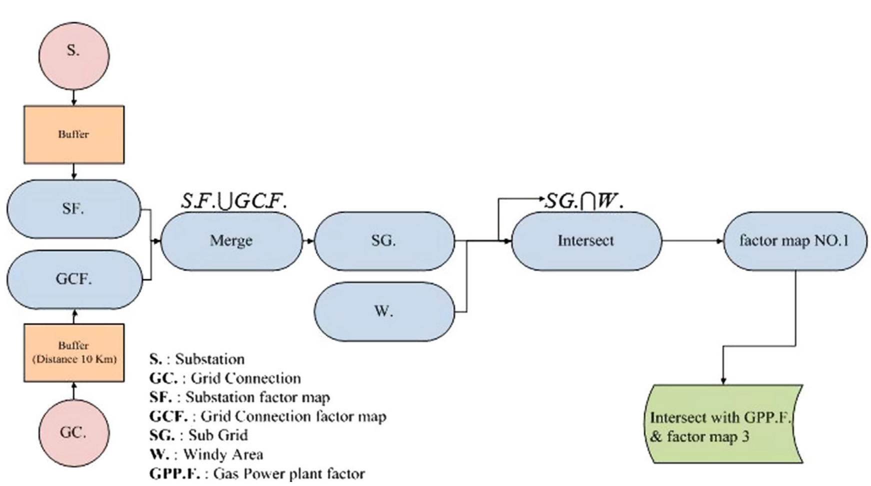

Fig. 4. Wind energy resource and grid connection availability site selection flow diagram.

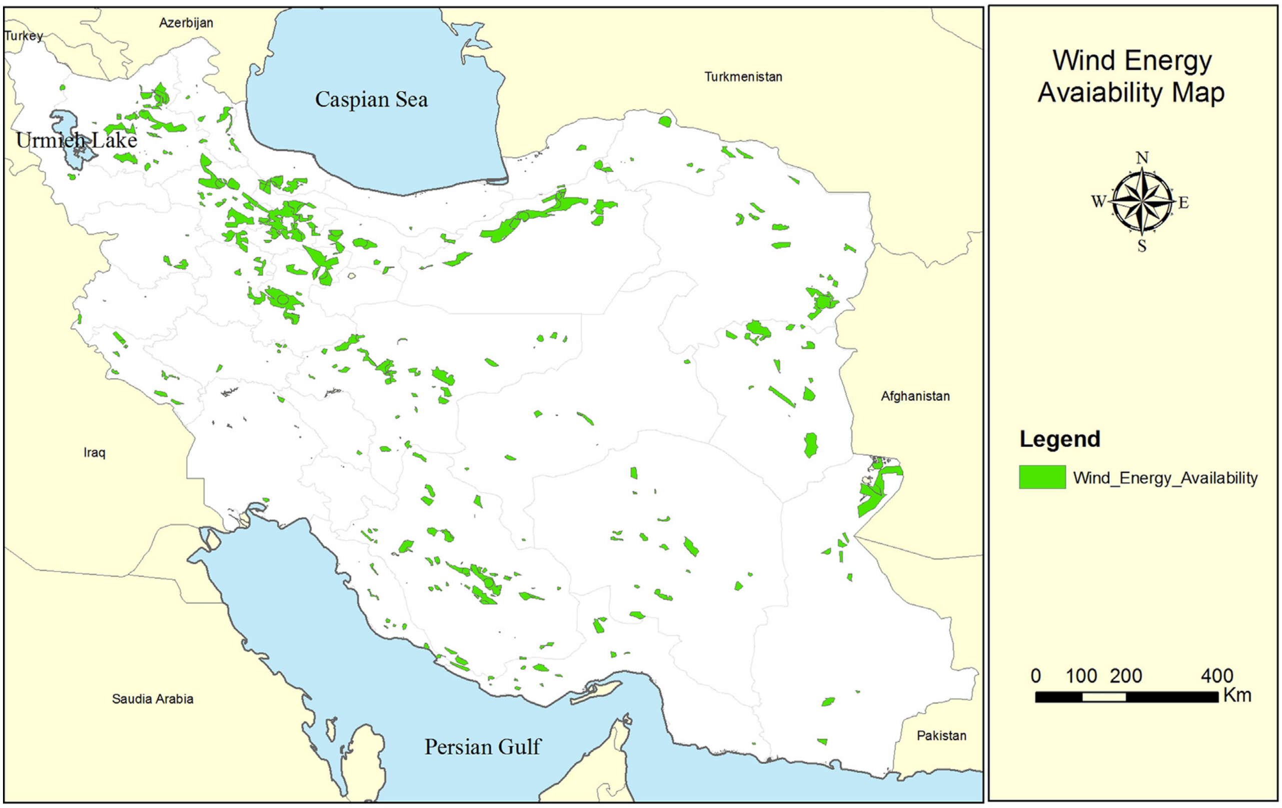

Fig. 5. Wind energy resource and grid connection availability map.

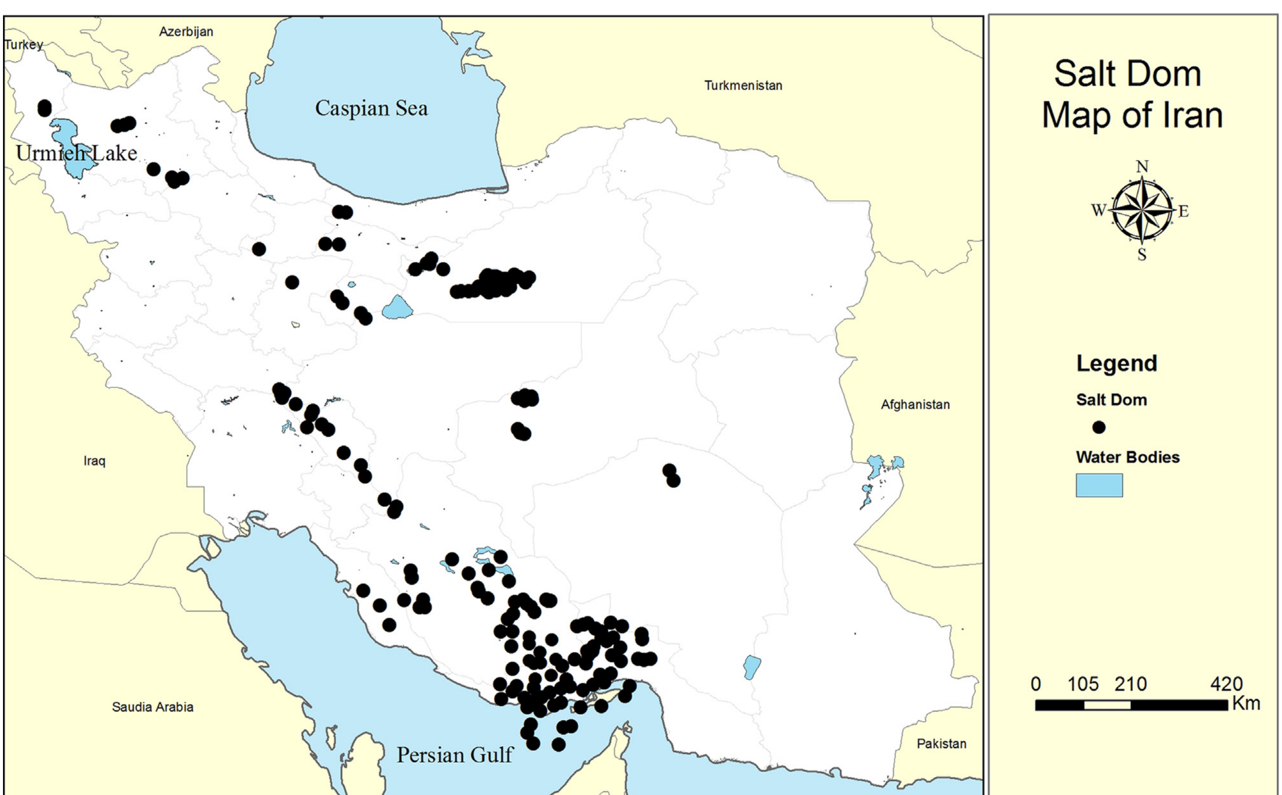

Fig. 6. The locations of salt domes on Iran wind area.

and Fig. 4.

$$\text{WEA} = ((\text{SF} \cup \text{GCF}) \cap \text{WF}) \quad (1)$$

Fig. 5 shows primary electricity (wind energy) production and power grid connections for suitable sites (Factor Map 1). The top 15 provinces were Qazvin, Zanjan, West Azerbaijan, East Azerbaijan, Bushehr, Fars, Qum, Hormozgan, Semnan, Yazd, Zanjan, Esfahan, Khorasan, Sistan-Baluchistan and Gilan. These provinces comprise 62,961 km^2 of the country (1,623,000 km^2), or about 4%, that are suitable locations selected using the first sub-model. The most promising sites were located in northwest Iran.

5.2. Thermal power plant and energy storage availability

All wind-CAES power plants must be located in proximity to salt domes for storage of compressed air, so only salt domes located in windy areas were included. Fig. 6 shows the locations of salt domes on the Iran wind atlas [16]. The parameters selected

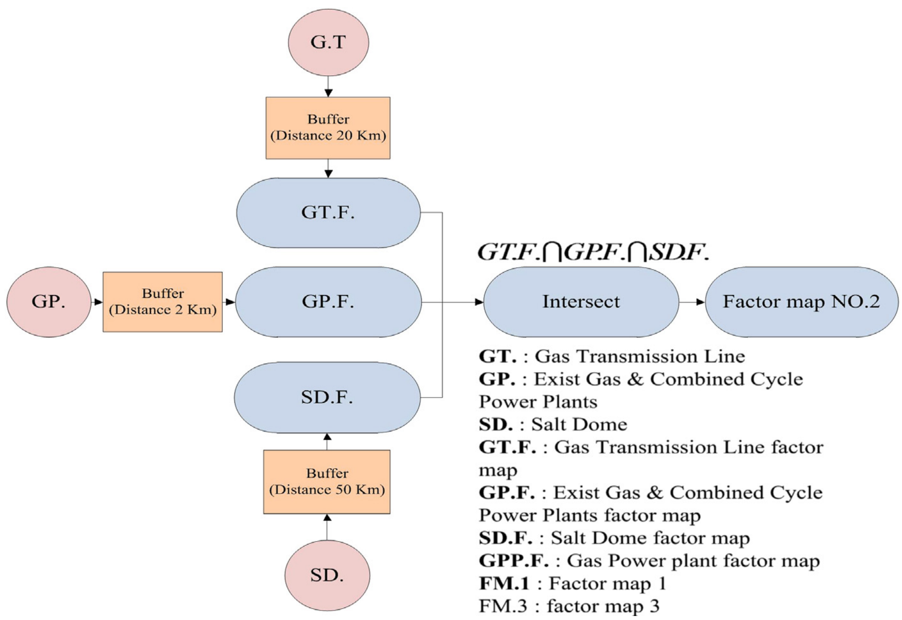

Fig. 7. Thermal power plant and energy storage possibility sub-model flow diagram.

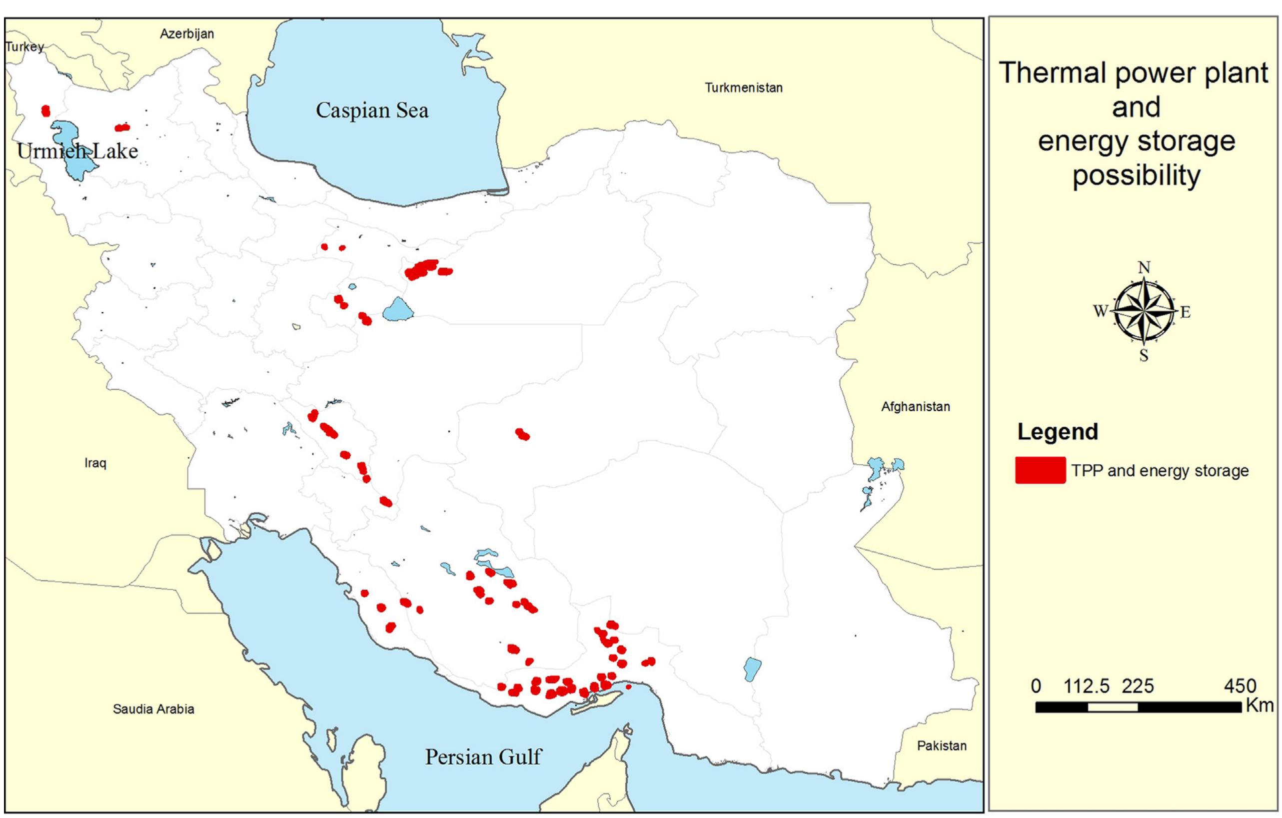

Fig. 8. Thermal power plant and energy storage possibility map.

from Table 2 were gas transmission line (GT), existing gas and combined cycle power plants (GP) and salt domes (SD). Their factor maps were integrated to locate suitable sites based on the defined criteria. Buffering was done for the parameters in Table 2 and the factor maps were merged to provide the best sites. The result was called the thermal power plant and energy storage possibility (TPPESP) or Factor Map 2. The modeling was done using ArcGIS is shown in Fig. 7 and is defined in Eq. (2).

$$\text{TPPESP} = ((\text{GTF} \cap \text{GPF}) \cap \text{SDF}) \quad (2)$$

Suitable sites with accessibility to SD, GT and GP are shown in Fig. 8. The most suitable sites were located in Hormozgan, Bushehr, Charmahal and Bakhtiari, Yazd, Esfahan, West Azerbaijan, East Azerbaijan, Semnan, Fars, and Qum provinces. This comprises only 4633 km^2, or 0.3%, of the country.

5.3. Environmental-economic suitability

In this sub-model all the layers and criterions are important as environmental guidelines such as distance to access roads, grid lines and slope are considered and environmental regulations are applied. Also some of the criteria including distance to access roads, distance to grid lines, degree of slope, distance to water bodies and elevation from sea level directly increases the cost of installation of the wind farm. Also according to the magnitude of extractable wind energy or potential of the wind farm investment will be different and final power price reduces by scale of the project. It is proved that by increasing the distance from any of mentioned criteria in every geographical and economic condition the cost of the project elevated and depends on numerous factors that can be related linearly or nonlinearly to the distances or degree of slope. The calculation of economic effect of each factor on power price is out of the aim of this paper but for clearance dependence the effect of the project scale on power connection post installation cost is described latter.

The third sub-model considered distance from cities and residential areas (CL), accessibility of the sites to access roads (AR) and water bodies (WB). In addition, the limitations for land slope (*S*) and elevation (*H*) were also buffered (Table 2). The CLF, ARF, and WBF factor maps are shown in Fig. 9. Since the wind-CAES power plants must be located at least 2 km from CL [21–23], the CLF factor map was discarded and its output merged with the output of the intersections of the ARF, WBF, *H* and *S* data layers.

According to the data which was gathered from many projects in different parts of Iran, average price of integrating a power plant to power grid is 97 €/m [13]. Detailed average prices for installation of posts with different capacities are shown in Table 3.

By using an exponential regression, the price for installation of posts can be equated which is shown in Fig. 10. Due to this equation beside data from other resources [11], maximum viable

Table 3
Average prices for installation of posts with different capacities [13].

NO	Capacity of post (kV)	Average price (€)
1	20	158
2	63	1850
3	132	735
4	230	998
5	400	2757

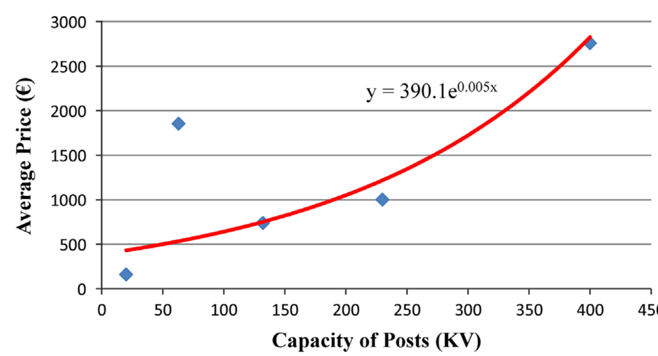

Fig. 10. Average price variations for installation of power connection posts with different capacities.

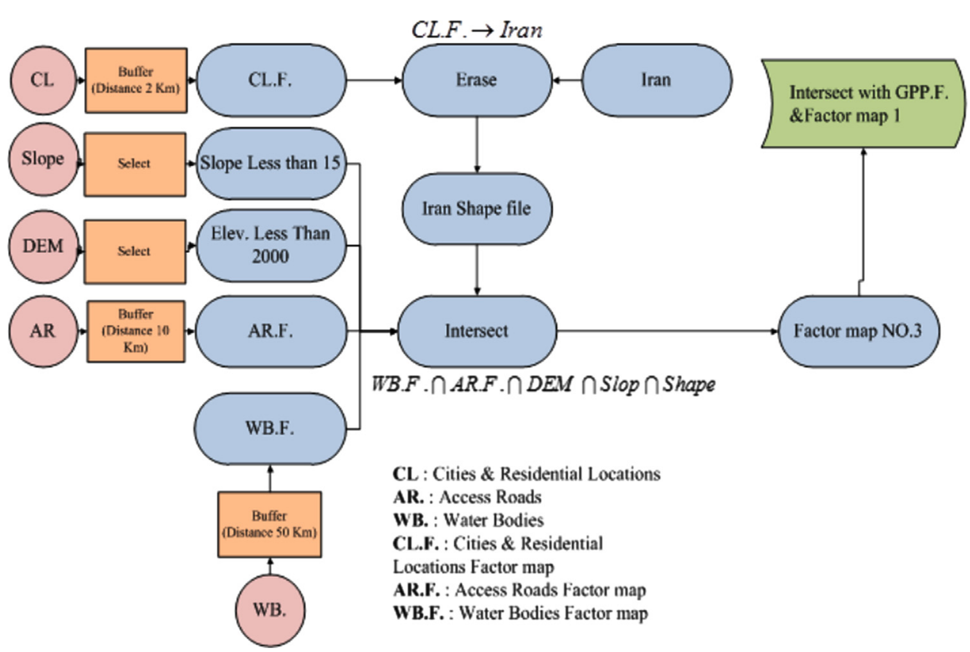

Fig. 9. Enviro-economical suitability site selection flow diagram.

distance of grid from power plant was estimated as 10 km as economical point of view. The final estimated value has been taken into account in producing this sub-model.

The final output was called environmental-economic suitability (EES) or Factor Map 3. It delineated sites with AR and WB that are at acceptable distance from CL with slopes of less than 15% and elevations under 2000 m using the Iran digital elevation model map (DEM) [24]. The process is shown in Fig. 9 and summarized with Eq. (3):

$$EES = (WBF \cap ARF \cap DEM \cap Slope) \cap (CLF) \quad (3)$$

Fig. 11 shows the results of the modeling. Most areas are located in the western and southern parts of Iran.

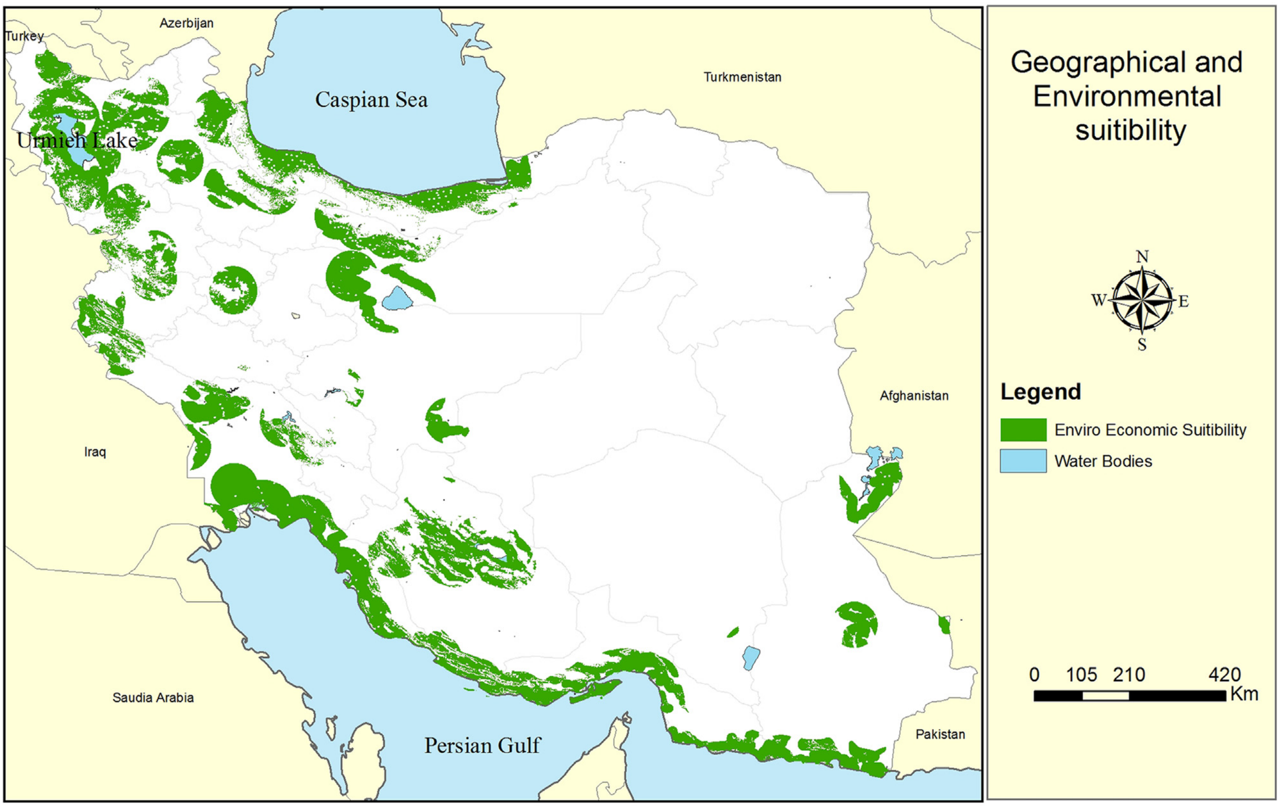

Fig. 11. Selected locations based on enviro-economical factors.

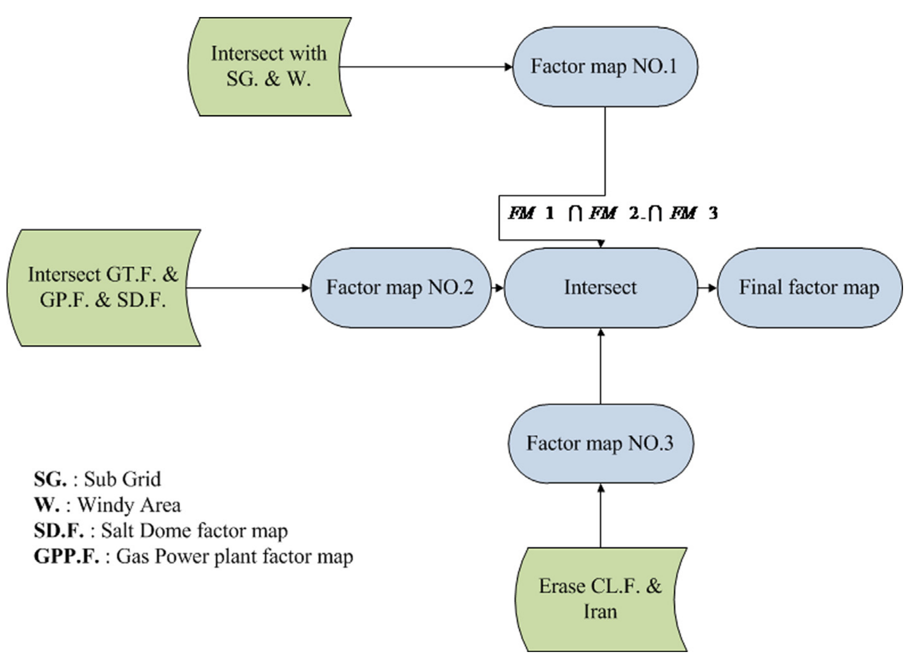

Fig. 12. The process or flow diagram final Wind-CAES power plants sites selection.

5.4. Wind-CAES power plant sites

In the final part of data integration, Factor Maps 1, 2 and 3 were integrated using Boolean logic and the locations of the wind-CAES power plants sites were defined. The flow diagram of the final site selection is shown in Fig. 12. Overlaying of the factor maps are defined in Eq. (4) [6,25]:

$$\text{Wind CAES power plant site} = (\text{WEA} \cap \text{TPPESP} \cap \text{EES}) \quad (4)$$

Eq. (5) is a linear programming function that shows the logic of the model. All parameters from the previous sections and their respective limitations from Table 2 are

$$\text{Min } Z = ((\text{SX}_1 + (\text{GC})X_2) \times W) \times ((\text{GT})X_3 \times (\text{GP})X_4 \times (\text{SD})X_5) \times ((\text{WB})X_6 \times (\text{AR})X_7 \times \text{DEM}X_8 \times \text{Slope}X_9) \times ((\text{CL})X_{10} - \text{Iran}) \quad (5)$$

Subject to

$$X_1 \geq 10,\ X_2 \geq 20,\ X_3 \geq 2,\ X_4 \leq 2,\ X_5 \geq 10,\ X_6 \geq 50,\ X_7 \geq 2,\ X_8 = 0,\ X_9 \leq 0.15 \text{ and } X_{10} \geq 2$$

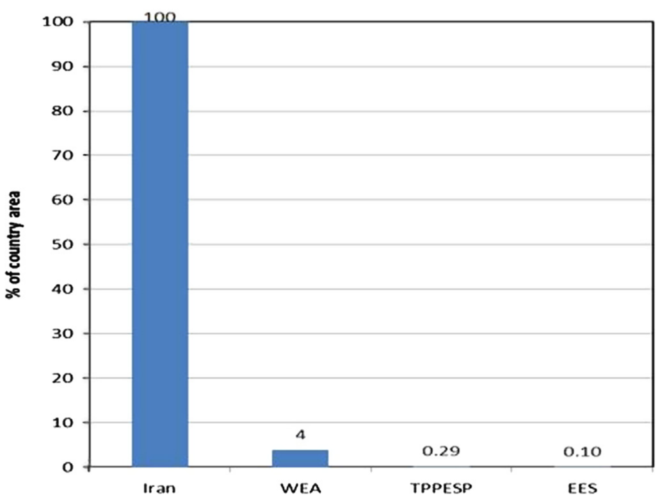

Fig. 13. The share of selected localities in every step using defined sub-models.

The model solved Eq. (5) using ArcGIS software. As shown in Fig. 13, a total of 30 suitable sites comprising 1682 km^2 (0.1% of the country) was selected as suitable for wind-CAES power plant sites. The suitable sites are clustered in five regions; two are located in Hormozgan and Bushehr provinces in southern Iran, two are in Fars and Qom-Tehran provinces in central Iran and one is in northwest Iran in East and West Azerbaijan provinces. Fig. 14 shows these five suitable sites in more detail.

All of the 30 suitable sites are summarized and described in more details in Table 4. The table also ranks the sites and provides their coordinates and names along with the average yearly wind speeds.

Stepwise location-based analysis is an effective method to minimize the study area and delineate Wind-CAES power plant locations. Fig. 15 shows the selected localities in every step using the defined sub-model.

6. Conclusion

The objective of this study was to identify wind-CAES power plant sites in Iran. Site selection considered globally available data

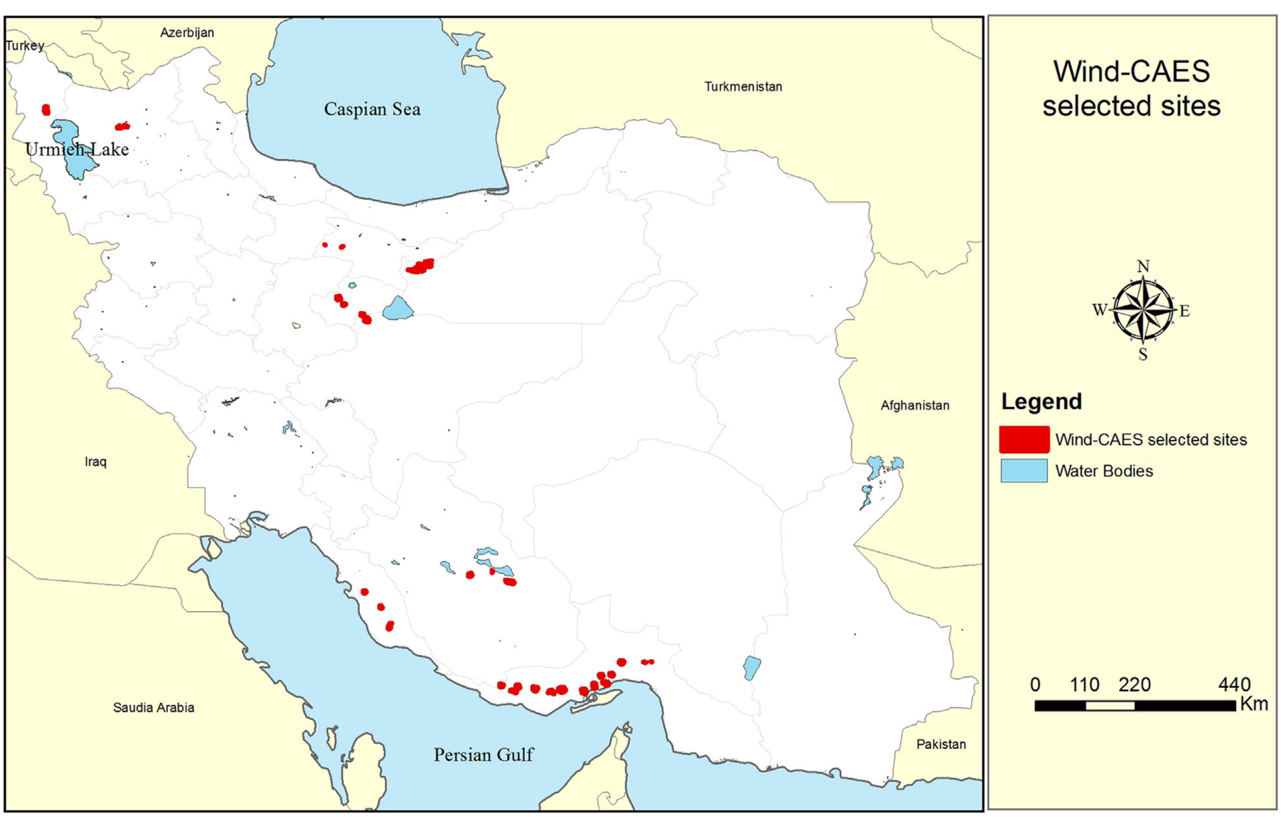

Fig. 14. Wind-CAES suitability map.

Table 4
Selected allowable sites for installing Wind-CAES power plants.

No.	Name	Province	Longitude latitude	Area	Closest city	Average wind speed annual (m/s)
1	Khoormoj	Bushehr	51.5694° 28.6418°	28136656	Khoormoj	> 7.2
2	Tabriz	Azarbaijan East	46.2845° 38.1924°	33624370	Tabriz	> 7.1
3	Tabriz_Khajeh	Azarbaijan East	46.5127° 38.1306°	25203048	Khajeh	6.8–7.1
4	Ghapoloq	Azarbaijan West	44.9120° 38.4273°	81132079	Khoy	> 6.2
5	Sarvestan	Fars	53.2812° 29.3086°	42427705	Sarvestan	6–6.3
6	Dashti	Bushehr	51.6996° 28.2639°	49600268	Bordkhoon	> 6
7	Yazdan	Qom	50.6911° 34.7584°	63272801	Yazdan	5.8–6.5
8	Govar	Fars	55.0573° 27.5711°	5744196	Govar	5.8–6.2
9	Kahnooieh	Hormozgan	54.2144° 27.0654°	68075245	Kahnooieh	5.6–6.2
10	Kashan	Esfehan	51.2360° 34.3270°	112856960	Kashan	5.8–6
11	Fasa 2	Fars	54.1378° 29.1434°	35570742	Fasa	5.5–6
12	Fasa1	Fars	54.0075° 29.1519°	21030287	Fasa	5.5–6
13	Jenah	Hormozgan	54.1120° 26.9550°	57671749	Daarbast	> 5.8
14	Dargoor	Hormozgan	55.7259° 27.0827°	84708303	Khamir	5.1–5.8
15	Hiroo	Hormozgan	55.0921° 27.0281°	131034981	Hiroo	5–5.8
16	Hara	Hormozgan	54.8689° 26.9157°	67982891	Hara	5.5–6
17	Kalat	Hormozgan	55.5350° 26.9730°	73721093	Khamir	5–5.6
18	Garmsar	Semnan	52.1597° 35.2445°	250672633	Garmsar	5.3–5.5
19	Roodeshoor	Hormozgan	54.5936° 27.0134°	82423859	Koverdan	4.7–5.3
20	Qom	Qom	50.7812° 34.6209°	29944114	Qom	5.8–6.5
21	Bastak1	Hormozgan	53.8950° 27.0907°	46084331	Bastak	5–5.6
22	Bandar abas1	Hormozgan	55.9638° 27.1309°	83124500	Bandar abas	5–5.5
23	Bandar abas2	Hormozgan	55.8675° 27.2841°	83124491	Bandar abas	5–5.5
24	Bandar abas3	Hormozgan	56.0779 27.3053	51625418	Bandar abas	5–5.5
25	Bandar abas4	Hormozgan	56.2776° 27.5480°	46787759	Bandar abas	5–5.5
26	Dehmobarez1	Hormozgan	56.7351° 27.5503°	65842335	Bandar abas	5–5.5
27	Dehmobarez2	Hormozgan	56.8622° 27.5596°	7705741	Bandar abas	5–5.5
28	Boushehr_Ahram	Boushehr	51.1908° 28.9385°	31174360	Ahram	5–5.5
29	Eshtehard	Tehran	50.4094° 35.8033°	1283795	Eshtehard	5–5.5
30	Mahdasht	Tehran	50.7535° 35.7609°	2956047	Mahdasht	5–5.6

and criteria for electrical grid connection, substation locations, gas transmission lines, wind atlas, salt dome specifications for storing compressed air, proximity of water bodies and access roads, distance from residential areas, land slope and elevation.

First the defined and generated data layers by ArcGIS software were categorized into three sub-models. These were: (a) wind energy resource and grid connection availability, (b) thermal power plant and energy storage availability and; (c) environmental-economic suitability. All sub-models were integrated to generate the final suitability map for wind-CAES power plant locations.

The model selected 30 suitable sites in a total of 1682 km^2 as suitable locations for wind-CAES power plants. As seen in the final map (Fig. 13), the suitable sites were clustered in five zones: two are located in Hormozgan and Bushehr provinces in southern Iran, two are in Fars and Qom-Tehran provinces in central Iran and one is in northwest Iran in East and West Azerbaijan provinces.

The model is shown to save energy and preserve the wind electricity in off-peak times, allowing peak-shaving using wind-CAES power plants. Future study should be to choose one site with

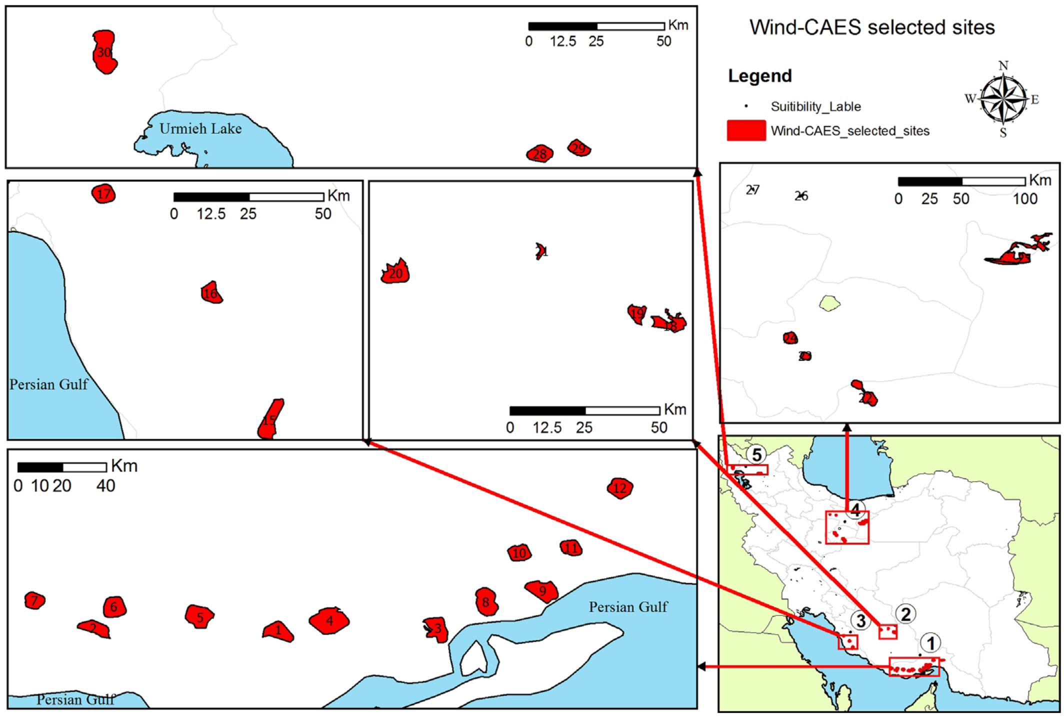

Fig. 15. The five suitable sites for Wind-CAES in more detail.

good capacity for a CAES power plant from the results of the model and analyze the effects of the wind farm after integration with a CAES power plant.

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